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POSSIBLE EVIDENCE FOR COLLECTIVE FLOW IN CENTRAL
HIGH ENERGY NUCLEAR COLLISIONS

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Nuclear Fluid Dynamics versus Intranuclear Cascade--
Possible Evidence for Collective Flow
in Central High Energy Nuclear Collisions

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Abstract:

We compare the predictions of a variety of current theoretical models of high energy nuclear collisions and contrast these results with recent experimental data for central collisions of ^{20}Ne on ^{238}U at E_{LAB} = 393 MeV/n. The experimental observation of broad sidewards maxima in the angular distributions of low and medium energy protons is reproduced by a nuclear fluid dynamical calculation with final freeze-out of the protons. In contrast, the current intranuclear cascade and simplified collision models predict forward peaked angular distributions.

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High energy nuclear collisions offer a unique opportunity to probe the properties of nuclear matter at high density and temperature. However, the program to extract information on the bulk properties of nuclear matter, such as the equation of state, from the experimental data requires precise knowledge about the dynamics of the collision process.

It has been pointed out that the large pressure in the high density, high temperature matter should cause a collective hydrodynamical sideways flow [1,2]. Indeed, quite early experiments [2] using particle track detectors reported sidewards maxima in the angular distributions of medium energy α-particles emitted for high multiplicity selected, i.e., central, collisions. On the other hand, inclusive, i.e., impact parameter averaged, data [3,4] on light fragment emission do not show sidewards peaked angular distributions. However, the measured azimuthal correlations between light and heavy fragments [5] exhibit signatures of the hydrodynamical bounce-off effect [6,7], and so do the two proton correlations [8] in heavy systems.

From the inclusive data [3] it was in general not possible to differentiate between the different existing dynamical models. Possible differences are washed out by the impact parameter averaging [9]. Hence, recent high multiplicity selected, i.e., central collision data [10] for Ne (393 MeV/n) + U $\rightarrow$ light fragments have received great attention. It is the purpose of the present work to compare the predictions of several distinct model calculations for this reaction and to provide a test of these models by a direct confrontation with the experimental data [10]. The models we use are two versions of the macroscopic nuclear fluid dynamical NFD model [11,12], two versions of the microscopic intranuclear cascade (INC) calculations [13,14], and two thermal models with a simplified participant-spectator geometry [15,16].

Let us briefly survey the various models used for our comparison. Both versions of the fluid dynamical approach solve numerically the equations of motion of an Eulerian fluid [6,7]. These equations express the conservation of the baryon number, momentum, and energy for a classical fluid. The validity of such an approach requires that the nucleon's mean free path λ is much less than the systems dimensions D. For peripheral collisions, the average number of scatterings $\langle n \rangle \sim D/\lambda \sim 1$, and hydrodynamics is unlikely to apply. However, for central collisions, $\langle n \rangle$ can be much larger than 1, in particular if high compressions are achieved [1]. Thus, the best chance for hydrodynamics to be applicable is clearly in central collisions of the heaviest available nuclei. Some quantum mechanical effects, such as the Fermi pressure and exchange terms are included through a realistic nuclear equation of state, which serves as the only input into the model. The nuclear viscosity, thermal conductivity, and a possible initial transparency are neglected, as well as hadron production and single particle effects.

In the first set of NFD calculations [11], long-range interactions are neglected. The initial nuclei have a sharp cut-off surface. The relativistic equations of motion are integrated using a particle-in-cell (PIC) method [7] with improved numerical accuracy [11]. The energy and angular distributions are calculated from the particle density and velocity vectors at a time sufficiently long so that the residual thermal energy is negligible, i.e., the densities are very small [11]. However, calculations based on transport theory indicate that during the expansion the thermal equilibrium can only be maintained until the fluid reaches the break-up density $\rho_{BU}/\rho_0 \approx 0.3\text{-}0.7$ [17]. Then the system breaks up into free particles, which reach the detectors with the momentum distribution they had in this freeze-out moment.

The incorporation of this freeze-out concept is the most prominent difference between the two applied versions of the NFD model. In the second NFD approach [12], the particle spectra are calculated by transforming the internal thermal momentum distribution of each fluid element at the break-up density with the corresponding collective flow velocity into the laboratory. Proton distributions are calculated by suppressing the emission of bound nucleons with internal energy $\varepsilon < m_p c^2$ [12]. This model also incorporates [6] realistic surface and binding properties via long-range Coulomb and Yukawa potentials [6]. The nonrelativistic equations of motion are integrated via the flux-corrected-transport (FCT) method [6].

The second class of models we consider are the relativistic intranuclear cascade approaches [13,14,18,19]. They are based on the classical impulse approximation, i.e., a nucleus-nucleus collision proceeds as a sequence of independent two particle collisions. The only input are the measured free nucleon-nucleon scattering cross sections. The scattered particles follow straight line trajectories until they interact again. This approach neglects the n-n potentials, which form the essential ingredient of the much more complex classical equations of motion calculations [18,20], as well as all many body interactions, which can be considerable for the high densities considered. Besides some attempts to include the Pauli blocking, the microscopic approaches are classical. Initially, the nucleons reside in potential wells, having the momentum distributions of a degenerate Fermi gas. The nuclei are spherical with diffuse surface. Reflection and refraction of the cascade particles at the nuclear surface and evaporation from the residual nuclei are neglected.

In the first cascade approach [13], the target and projectile nuclei are treated initially as continuous Fermi seas of nuclear matter. The collision process starts via the interactions between projectile Fermi-sea and target Fermi sea nucleons forming cascade particles, each of which has a continuous Gaussian density distribution. They leave a hole in the initial nuclear density distributions. In the course of the collision process, interactions between cascade and Fermi sea particles, as well as between cascade particles, can occur, with the restriction that two given cascade particles cannot interact more than once, unless at least one of them has interacted with a third particle. Pion production and absorption is included via Δ_{33} formation, decay and capture.

In the second version of the cascade model [14], the nucleons are represented by point-like particles and are initially assigned random positions and momenta in the nuclei. The nucleons interact at the point of closest approach if their separation d satisfies $\pi d^2 \leqslant \sigma_{tot}$ (E_{CM}), where σ_{tot} is the appropriate n-n total cross section, which depends on the center of mass energy of the n-n pairs. If this condition is satisfied, the scattering angle is randomly chosen from experimental elastic scattering angular distributions. Inelastic n-n collisions, Δ_{33} and pion formation are neglected.

The third class of models we consider is based on the simplified participant-spectator geometry [21]. These models provide an easy, semi-analytic analysis of inclusive data. The firestreak model [15] allows for a calculation of the spectra of different light fragments (p,d,t...) emitted, by assuming thermal equilibrium in streaks of nuclear matter. The second approach, the two component--direct plus thermal--model [16], takes into account, in addition to the thermal nucleon component, the single scattering contribution, which is appreciable at intermediate energies and forward angles.

All the models discussed above are classical. The only existing self-consistent quantum mechanical approach, the TDHF model, can only be applied up to bombarding enegies E_{LAB} < 100 MeV/n [22], because of the mean field approximation involved.

Figure 1 shows the angular distributions of protons emitted from central collisions of Ne (393 MeV/n) + U. The various models discussed above are compared and confronted with the experimental data [10]. The central collision data have been obtained by triggering on the highest 15% of the multiplicity distribution associated with a 90° proton. This trigger corresponds to roughly 15% of the inclusive cross section [10]. Using the participant-spectator geometry, this leads to a cutoff impact parameter b^{max} = 1.5 fm [16]. This small value (used in the macroscopic calculations shown at the right-hand side of Figure 1) arises from the large contribution of small impact parameters to high multiplicity inclusive events [16]. The NFD model with thermal break-up and the firestreak model allow for a calculation of the actual proton spectra. The remaining models yield the sum of charges (p + d + t + 2^{3}He + ...) distributions only. However, the preliminary data [23] on central selected d and t exhibit similar spectra as the protons shown in Fig. 1. In particular, the sum of the p, d and t angular distributions exhibit the same sidewards peaking as the proton distributions; only the absolute magnitude is changed. Hence, the <u>shape</u> of the proton angular distributions rather than the absolute magnitude should be compared to the calculated sum of charges distribution.

The data exhibit broad sidewards maxima at large angles, which shift forward with increasing proton (or d,t) energy. In comparison, the NFD model without thermal break-up [11], although yielding a sidewards peak structure, fails to explain the data in several respects: It gives an about one order of magnitude too large peak at low energies, $E < 50$ MeV, too few high energy particles, the peaks are clearly too narrow, and the peak positions shift to somewhat larger angles with increasing proton energy, opposite to the trend in the data.

On the other hand, the NFD model with break-up included [12] describes the data reasonably well, in shape as well as in magnitude. The energy spectra exhibit a similar flatness as the data. This agreement with data demonstrates the importance of a proper treatment of the break-up stage [12,24].

Next we discuss the results of the cascade models. The results of cascade 1 [13] are based on a high multiplicity selection, $M \geqslant 21$, while those of cascade 2 [14] are for exactly central collisions. For this reason, the shapes of the angular distributions should be compared rather than their absolute values.

In sharp contrast to the NFD calculations, both cascade models exhibit forward peaking and thus fail to reproduce the salient features of the data. It is important to emphasize the insensitivity of the cascade results to variations in the multiplicity cutoff and to different impact parameter cutoffs. In fact, we find that peripheral, inclusive, and central selected angular distributions in this model [13] all exhibit the same, forward-peaked shape of the angular distributions, in strong contrast to the data [10]. This qualitative failure of the cascade model points towards the necessity of a more realistic treatment of the nuclear interactions, including for instance mean field effects as in the classical equations of motion approach [20].

Finally, we consider the near-analytic models. Both the firestreak and the two-component model exhibit forward peaked distributions, in contrast to the data. It should be pointed out, however, that the relative yields of p, d and t as calculated in the chemical equilibrium firestreak model [16] agree reasonably well with the preliminary data [23]. The direct nucleon component [16] produces a slight sidewards peak at very small angles beyond a proton energy of 140 MeV only (not shown here). Note the agreement between the thermal and the cascade models, indicating a large degree of thermalization in the latter.

In summary, we presented the first detailed comparison between various theoretical calculations and the central collision data for Ne (393 MeV/n) + U. The main qualitative feature of the data that we focus on is the observed broad sidewards maxima in the angular distributions of low and medium energy protons. This qualitative feature is not accounted for by existing intranuclear cascade or thermal models. On the other hand, the hydrodynamical models predict sidewards emission due to collective matter flow. We find a qualitative agreement of the NFD-model with the data once the thermal breakup is included into the calculation. Our main point is to emphasize the qualitative difference between the sidewards emission predicted by hydrodynamics and the forward peaking of models without collective flow. The present proton (d,t) data tend to support the existence of collective matter flow. However, with the proton data alone no definite conclusion can be reached because the proton spectra are sensitive to the mechanism of composite formation. In particular, a large probability for composite production in the forward direction could lead to forward suppression of free protons even though the sum of charges remains forward peaked. Therefore, it will be essential to measure the spectra of heavier composites ($Z \geqslant 2$) [2] in central collisions to establish conclusively the existence of a collective sidewards flow in high-energy nuclear collisions.

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Figure Caption

Figure 1 shows the angular distributions of protons emitted from central collisions of Ne (393 MeV/n) + U. The numbers in the figure indicate the kinetic energies of the emitted fragments in MeV. The data (middle left frame) exhibit broad sidewards maxima, in contrast to the cascade calculations 1 [13] and 2 [14] (upper and lower left frame), which yield forward peaked angular distributions. The results of cascade 1 are obtained using a high multiplicity selection, $M \geqslant 21$, while those of cascade 2 are for exactly central collisons.

The two component model [16] (long dashed curves) and the firestreak calculations [15] for protons (p, solid curves), d (short dashed), t (dotted), and ^{3}He (dashed-dotted) are shown in the upper right frame.

The hydrodynamic calculations 1 [11] without thermal breakup (lower right frame) yield too narrow angular peaks with the energy spectra falling off much too steeply. The calculated low energy $E < 50$ MeV distributions overestimate the data by more than an order of magnitude and are not shown here. The NFD model with thermal break-up [12] (middle right frame) gives a reasonable description of the broad sidewards maxima and their forward shift with energy. The dashed curve shows the enhanced sidewards peaking for the sum of charges distribution at $E_{KIN} = 30$ MeV/n. The curve is multiplied by 0.2.

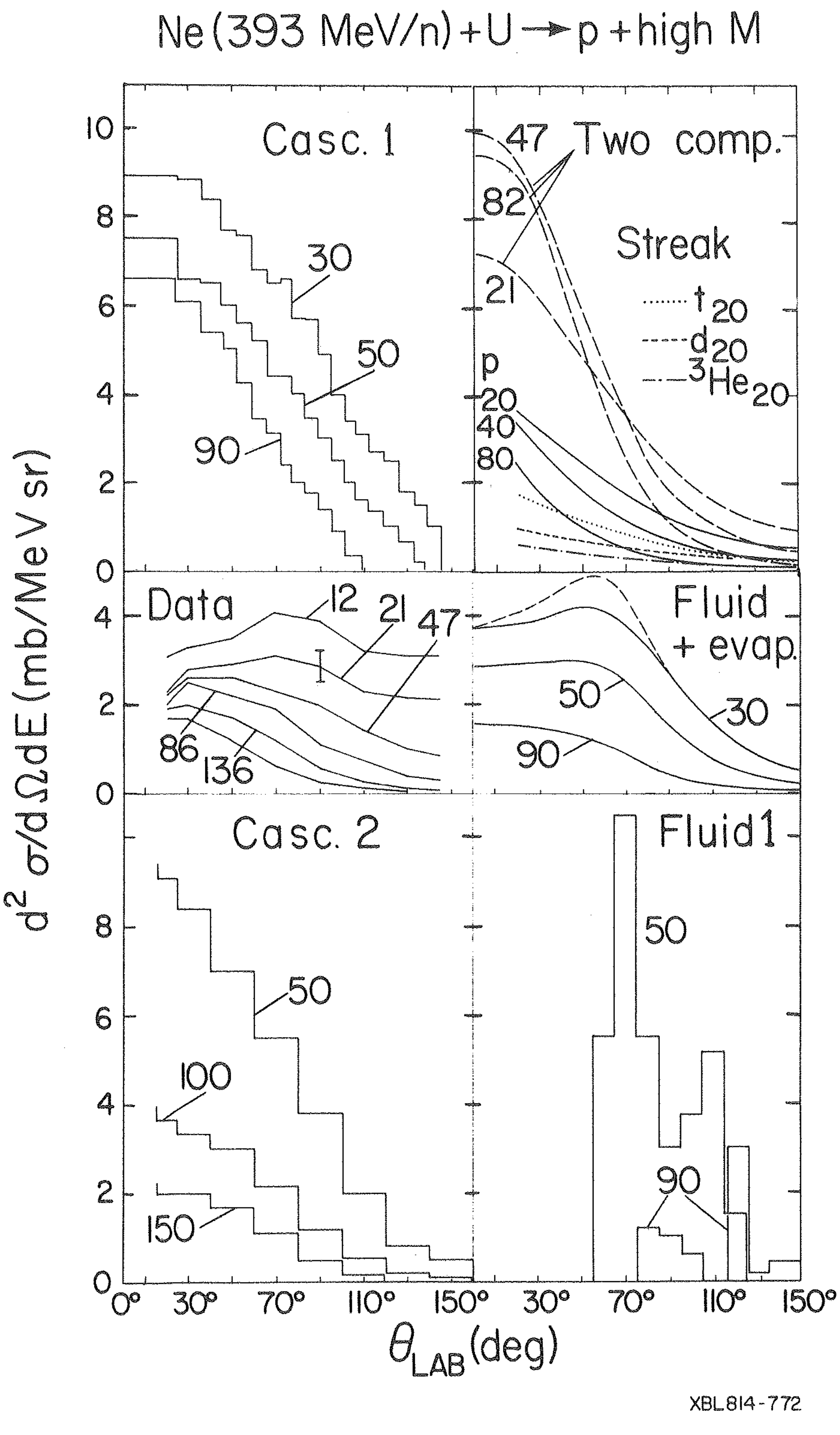
Ne(393 MeV/n)+U → p+high M
Casc. 1
30
50
90
Two comp.
47
82
21
Streak
t20
d20
3He20
p
20
40
80
Data
12
21
47
86
136
Fluid
+ evap.
50
30
90
Casc. 2
50
100
150
Fluid1
50
90
d2 σ/dΩdE (mb/MeV sr)
θLAB (deg)
0° 30° 70° 110° 150°
XBL814-772

Fig. 1